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AN EFFECT OF SWEEP ANGLE ON ROLL DAMPING DERIVATIVE FOR A DELTA WING WITH CURVED LEADING EDGES IN UNSTEADY FLOW

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ABSTRACT

This paper presents the results of an analytical study to account the effect of the sweep angle of a delta wing whose leading edges are curved on roll damping derivative at various angles of attack and the amplitude of the full sine waves. In the present theory, the effect of Leeward surface has been taken into consideration with the attached shock case at the leading edge. For a detached shock case, this theory will not be valid. Results have been obtained for the hypersonic flow of perfect gases over a wide range of angle of attack and the Mach number. The results indicate that the roll damping derivative decreases with a sweep angle, but increase with the increase in the flow deflection angle δ as well as with Mach M.

KEYWORDS: Curved Leading Edge, Delta Wing, Hypersonic & Sweep Angle

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Original Article

1. INTRODUCTION

The intangible desire to explore the space has become universal and designing the spacecraft is on the top priority. With the requirement of high-performance aircraft, the importance of research has been shifted to the field of hypersonic flow. At the preliminary design stage, the knowledge of aerodynamic load and stability derivatives facilitating the design process of delta wings is of the most important aspect. In this regard, the present study has been taken up to relate the influence of the angle of sweep on damping stability derivative due to the rate of roll of a delta wing whose edges are curved.

Ghosh [1] has developed a 2D large deflection hypersonic similitude. The resulting piston theory is not restricted to slender shapes as in the cases of Lighthill's [2] and Miles [3] piston theories. Ghosh's piston theory [4] has been applied to oscillating plane ogives to predict C_{m_q}. The similitude was extended to non-slender cones/quasi cones, and a new kind of piston motion, called conico-annular piston motion was given by Ghosh [5]. Oscillating delta wings at large incidence was treated by Ghosh [6]. Etkin [7] and Levin [8] have shown the separate effects of the pitch rate and incidence rate on the pitching moment. The plane piston theory of Ghosh [9] was applied with the inclusion of the wave reflection effect to obtain in closed form $C_{m_{\dot{\alpha}}}$ for non-slender

wedges/plane ogives with the rate of α in hypersonic flow.

Ghosh [10] has given a unified hypersonic similitude, and a consequent piston theory which is valid for wedges/quasi-wedges for any Mach number greater than 1 and $E \le 0.3$ provided bow shock is attached. Hui et al. [11] have studied the problem of stability of an oscillating flat plate wing of arbitrary plan form placed at a specified mean angle of attack in supersonic/ hypersonic flow by applying strip a theory. During the derivations of the theory, it is assumed that at each spanwise station the flow is independent of the location of the strips, and the flow remains two-dimensional with the shock being attached.

To assess the overall stability the moment derivatives due to pitch rate as well as incident rate should be evaluated. In the present work, the unified similitude of Ghosh [12] along with the extended theory of Crasta & Khan [15]-[20] is combined with strip theory to obtain the unsteady moment derivative for a wing whose front edge is straight.

In this paper, the authors have attempted to study the Stiffness derivative with different pivot positions (h), which gives accurate results in comparison with the theory developed, by Liu as well as Crasta & Khan.

Crasta and Khan developed a theory to evaluate the stability derivatives in pitch, which does not cater to the unsteady effect as the theory developed by them is a quasi-steady one. However, the present theory presents unsteady flow, and the effect of sweep angle and the amplitude of full sine wave, with curved leading edges on the roll damping derivative is presented in this paper. The effect of lee surface is also taken into consideration.

2. ANALYSIS

Let the roll be p the roll rate and the rolling moment is L, defined according to the right-hand system of reference

$$L = 2\int_0^c \left(\int_0^{z=f(x)} pz dz \right) dx$$

The local piston Mach number normal to the wing surface is given by

$$M_P = (M_\infty) Sin\alpha_0 \frac{z}{a_\infty} \overline{p}$$

The roll-damping derivative is non-dimensionalized by dividing with the product of dynamic pressure, wing area and span and characteristic time factor

$$\therefore -C_{l_p} = \frac{1}{\int_\infty U_\infty C^3 b(\cot\varepsilon - \frac{4A_H}{\pi})} C^3$$

$$\therefore -C_{l_p} = \frac{\sin\alpha_0 f(S_1)}{(Cot^2\varepsilon - \frac{4A_H}{\pi}\cot\varepsilon)} \begin{bmatrix} \frac{\cot^2\varepsilon}{12} + \cot^2\varepsilon \frac{A_F}{2\pi} - \frac{A_H}{\pi^3}(\pi^2 - 4) + \\ \frac{1}{4}\cot\varepsilon(A_F{}^2 + A_H{}^2) - \frac{4}{9\pi} A_H{}^3 \\ -\frac{16}{9}\frac{A_F A_H}{\pi^2} - \frac{16}{15\pi} A_F{}^2 A_H \end{bmatrix} \quad (1)$$

Where $S_1 = M_\infty Sin\alpha_0$

$$f(S_1) = \frac{(\gamma+1)}{2S_1}\left[2S_1 + \frac{(B+2S_1^{\,2})}{(B+S_1^{\,2})^{1/2}}\right]$$

On the Leeward surface, the piston Mach number

$$M_p = \frac{Z_{\bar{p}}}{a_\theta \cos\mu_\theta}$$

For the rotation in the right-handed direction the acoustic pressure ratio

$$\frac{p_p}{P_\theta} = 1 + \gamma M_p$$

The rolling Moment

$$\bar{L} = -\int P_p (L-x) z dz$$
$$= \int \frac{p_\theta \gamma z}{a_\theta \cos\mu_\theta}(L-x) z dz$$
$$= \frac{p_\theta \gamma}{a_\theta \cos\mu_\theta}\int z^2 (L-x) dz$$

The evaluation of the above integral is precisely the same as Khan (1984) only the coefficient

$$\frac{p_\infty AF(S_1)}{a_\infty \cos\phi}$$

has been replaced here by

$$\frac{p_\theta \gamma}{a_\theta \cos\mu_\theta}$$

$$\therefore -C_{l_p} \textit{Contribution from Leeward surface} = R.H.S.of\,(1) * \frac{p_\theta \gamma}{a_\theta \cos\mu_\theta} \Big/ \frac{p_\infty AF(S_1)}{a_\infty \cos\phi}$$

$$= \frac{2p_\theta}{p_\infty}\frac{a_\infty}{a_\theta}\frac{M_\theta}{M_\infty}\frac{1}{\sqrt{M_\theta^{\,2}}-1}\frac{1}{(\cot^2\varepsilon - \frac{4A_H Cot\varepsilon}{\pi})}[\frac{\cot^3\varepsilon}{12} +$$
$$\cot^2\varepsilon(\frac{A_F}{2\pi} - \frac{A_H}{\pi^3}(\pi^2-4)) +$$
$$\frac{1}{4}\cot\varepsilon(A_F^{\,2}+A_H^{\,2}) - \frac{4}{9\pi}A_H^{\,3} - \frac{16}{9}\frac{A_F A_H}{\pi^2} - \frac{16A_F^{\,2}A_H}{15\pi}] \qquad (2)$$

$$\therefore -C_{l_p} = R.H.S\left[(1)+(2)\right]$$

3. RESULTS AND DISCUSSIONS

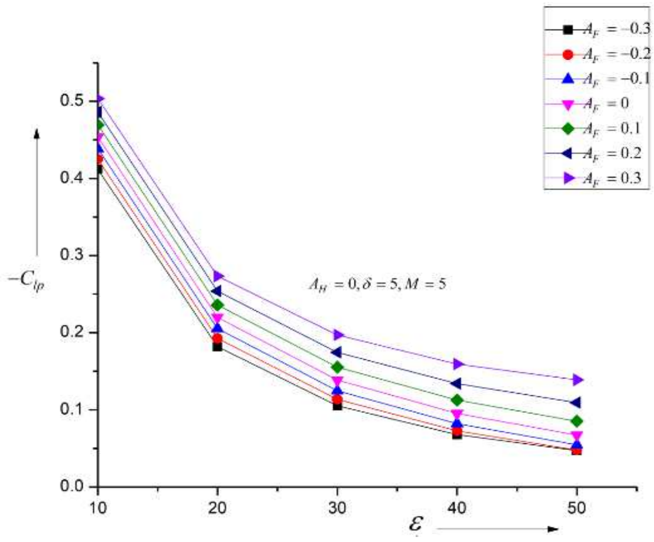

Figure 1: Rolling Derivative vs. Sweep Angle for δ = 50, M = 5

Figure 1 shows the variation of rolling derivative with a sweep angle (in the range from 10^0 to 50^0) for full sine waves for amplitude ± 0.3 for Mach number M = 5 and the angle of incidence of five degrees (i.e., $\delta = 5^0$). The rolling derivative decreases with the increase in the sweep angle and increases with the amplitude of the full sine wave for a fixed value of the inertia level of Mach 5. Given the increase in sweep angle, the planform area of the wing will decrease. However, an increase in the amplitude of the sine wave will result in a marginal increase in the planform area. It is well known that the aspect ratio of the wing is relatedto the span of the wing and the planform area. Since we are increasing the sweep angle for the different amplitude of the full sine wave and keeping the rest of the parameters of the wing remains the same. Also, it is seen that the initial decrease in the rolling moment derivative is very high for a sweep angle from ten degrees to twenty degrees. The reasons for this trend may be due to a decrease in the planform area at these sweep angles. Further, it is observed that the amplitude of the full sine wave is marginally more effective for sweep angles in the range from thirty to fifty degrees.

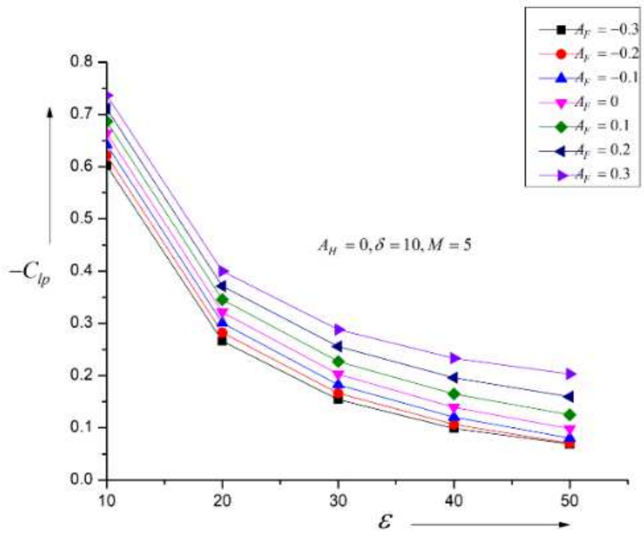

Figure 2: Rolling Derivative vs. Sweep Angle for δ = 100, M = 5

A similar result for the angle of attack of ten degrees is shown in Figure 2. The results show that due to the increase in the angle of attack there is a linear increase of

The roll damping derivative for a fixed value of the sweep angle is seen, and later with an increase in the sweep angle the Rolling derivative decreases with a sweep angle for full sine wave for δ = 10^0, M = 5. It is evident that there is a 20% increase in the magnitude of rolling derivative when the angle of attack increases from five to ten degrees and decreases with sweep angle. Initially for sweep angles 10 to 20 degrees, there is a steep decrement, and then smooth linear decrement is seen.

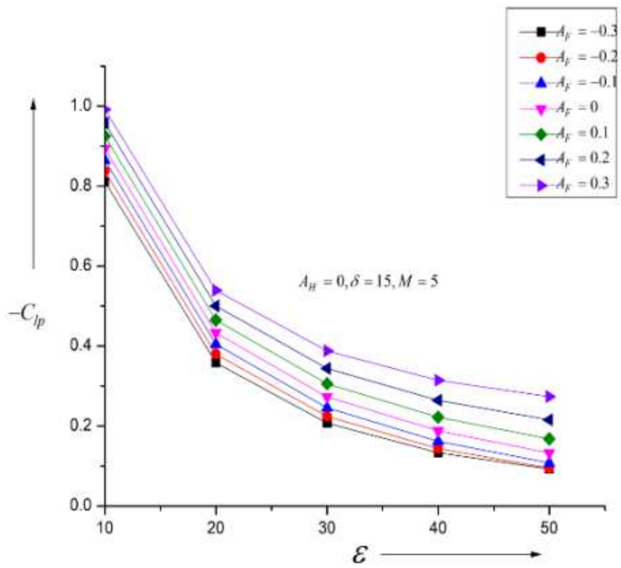

Figure 3: Rolling Derivative vs. Sweep Angle for δ = 150, M = 5

Figure 3 shows Variation of Rolling derivative with a sweep angle for the various amplitudes of full sine wave for δ = 15^0, M = 5. These results are similar to that for the angle of attack five and ten degrees. A higher magnitude of rolling derivative is found due to the increase in the angle of attack; it is evident from the expression of the rolling derivatives that trend will be linear with the increase in the angle incidence.

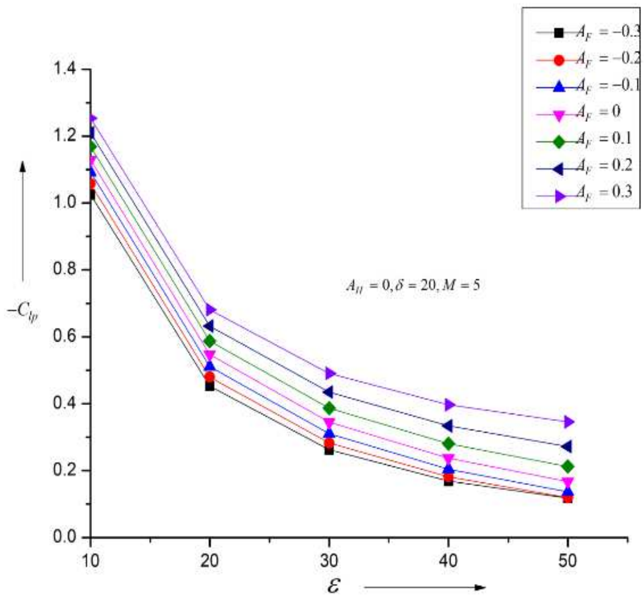

Figure 4: Rolling Derivative vs. Sweep Angle for δ = 200, M = 5

Figure 4 shows a variation of Rolling derivative with a sweep angle for the various amplitudes of full sine wave for δ = 20^0, M = 5. These results are similar to that for the angle of attack five and fifteen degrees. It is evident from the expression of the rolling derivatives that trend will be linear with the increase in the angle incidence.

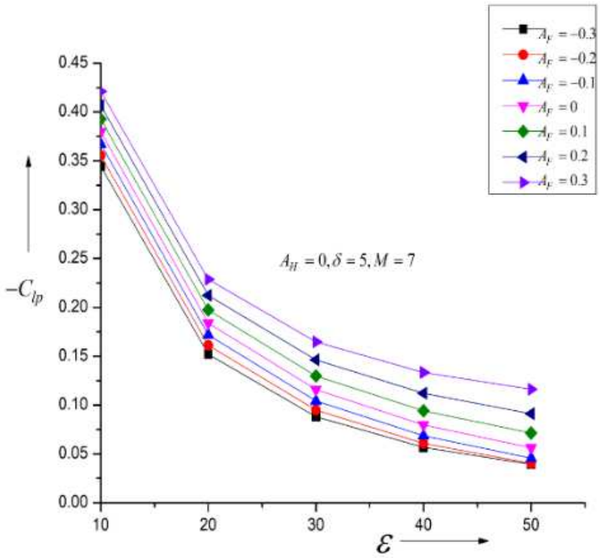

Figure 5: Rolling Derivative vs. Sweep Angle for δ = 5, M = 7

Figure 5 shows the change of the Rolling damping coefficient due to the rate of roll and increase in sweep angle for full sine wave for δ = 5, M = 7. When we compare the results of Figure 1 with Figure 5, in both the cases all the variables are identical except the inertia level, which was 5, has been enhanced to 7. We know that any increase in the Mach number from 5 will result in a decrease in the pressure variation on the surface of the wing leading to a decrease in the aerodynamic parameters, and the same has been observed. It is observed that as inertia level increases, there is a 10% increment in the numerical value of the rolling derivative. For higher sweep angles like 50 degrees and above the rolling derivative is very close to zero.

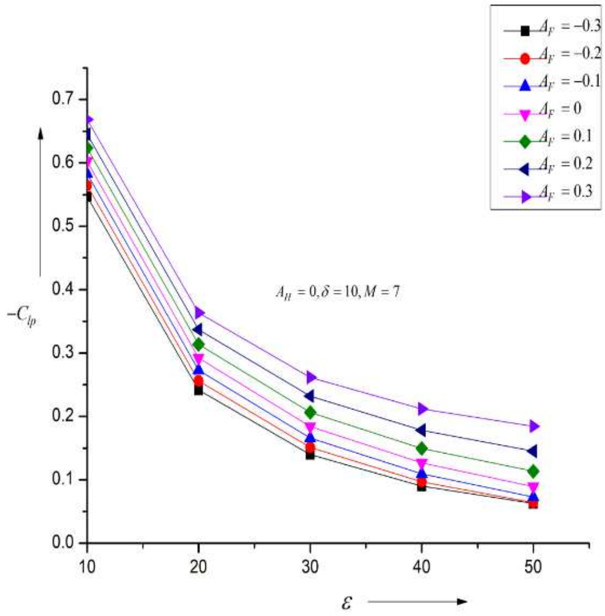

Figure 6: Rolling Derivative vs. Sweep Angle for δ = 10, M = 7

Figure 6 presents the changes rolling derivative with a sweep angle for full sine wave for 10 degrees semi vertex and Mach number 7. These results are similar to Figure 2. There is a 30% increase in the magnitude of rolling derivative when the flow deflection angle increases from 5^0 to 10^0. Otherwise, the same trend as in the previous figure is seen.

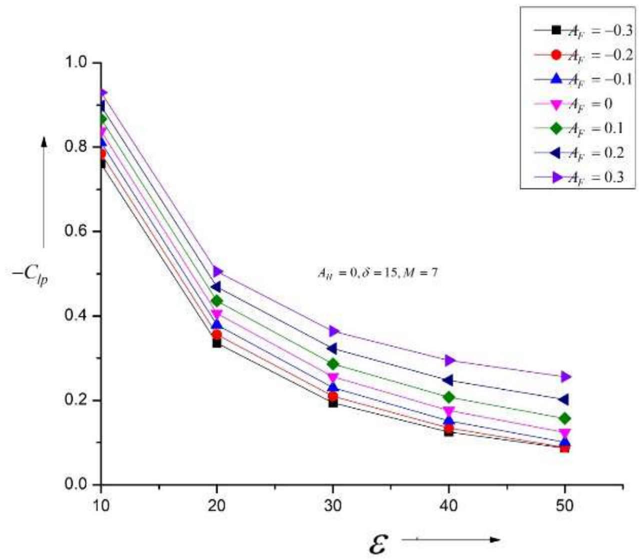

Figure 7: Rolling Derivative vs. Sweep Angle for δ = 150, M = 7

Figure 7 depicts the changes in the rolling derivative with a sweep angle for the angle of attack of 15^0 and Mach 7. This figure shows similar results as was seen Figure 3 except for an increased level of inertia. Since this Mach number and angles of attack, the magnitude of the rolling derivative is almost close to one and has maintained the higher magnitude, even at a higher sweep angle around fifty degrees.

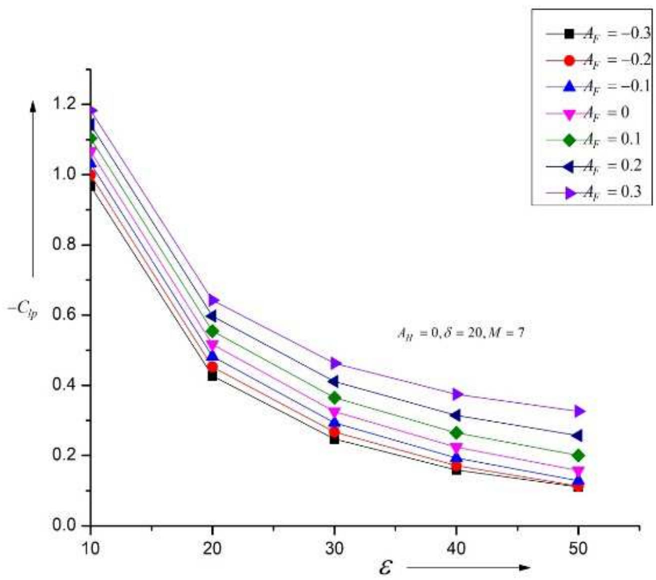

Figure 8: Rolling Derivative vs. Sweep Angle for δ = 200, M = 7

Figure 8 depicts the changes in the rolling derivative with a sweep angle for the angle of attack of 20^0 and Mach 7. This figure shows similar results for the cases when a full sine wave is superimposed on the straight leading edge as was seen Figure 7 except for an increased level of inertia and the flow deflection angle δ. The significant contribution in the increment of the damping derivatives due to the rate of roll and also, the increment in the flow deflection angle results in the increment of the surface area of the wing.

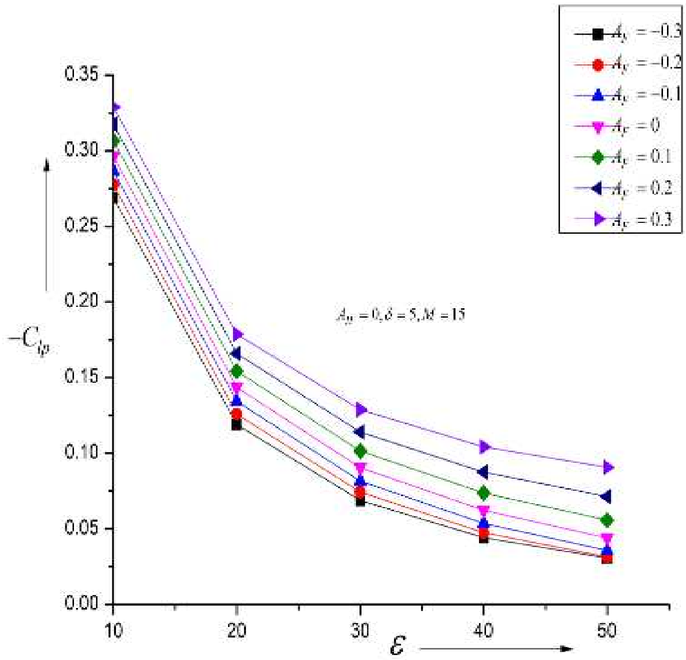

Figure 9: Rolling Derivative vs. Sweep Angle for δ = 50, M = 15

Figure 9 presents the rate of change of rolling derivative with a sweep angle for full sine wave for the angle of attack δ = 5 degrees and Mach number M = 15. For sweep angles, 10 to 20 degrees the magnitude of the rolling derivative shows a steep decrease in the damping derivative due to the roll rate p of the wing and further as sweep angle increases from 30 to 50 degrees the change in magnitude is 50%. The reasons for this trend may be due to a change in the surface pressure on the planform area of the wing. It is also seen that the rolling damping derivative is sensitive with the sweep angle as well as the planform area of the wing. Since in the present case due to increase in the amplitude of the sine wave the planform area will increase, and the variation in the damping derivative may occur because of the net effect of inertia level, sweep angle, the angle of attack and the planform area of the wing.

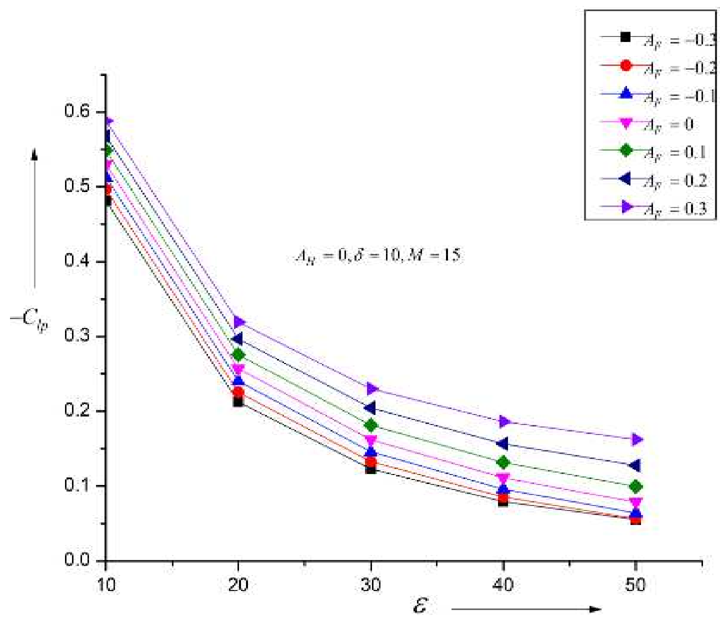

Figure 10: Rolling Derivative vs. Sweep Angle for δ = 100, M = 15

Similar results are shown in Figure 10 for Mach number M = 15 and angle of attack δ = 10^0. The only difference between this result and the previous result is that the magnitude of the roll damping derivative is being increased by fifty percent due to the increase in the angle attack from δ = 5 to 10. It is well known that with an increment in the angle the aerodynamic derivatives will decrease as roll damping derivative is a linear function of the angle of attack.

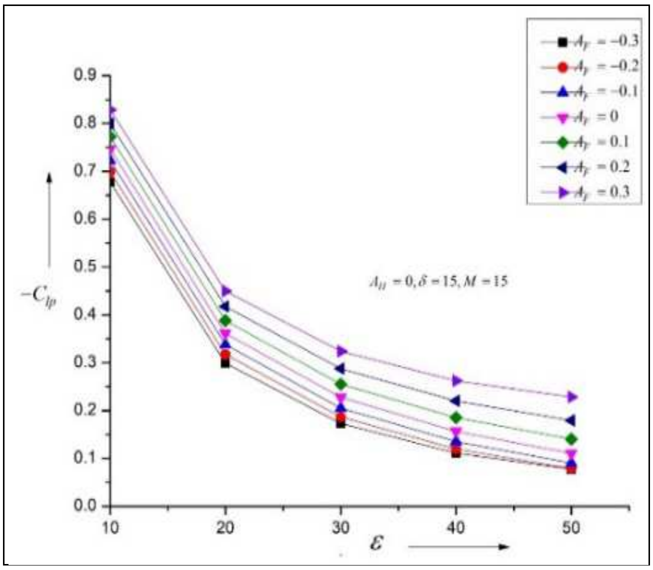

Figure 11: Rolling Derivative vs. Sweep Angle for δ = 150, M = 15

Figure 11 presents the rate of change of the rolling derivative with a sweep angle for full sine wave for the angle of attack δ = 15^0. Since the Mach number is very high, hence at such high Mach number the flow variables will no more depend on the Mach number and will remain constant. It is seen that for these flow conditions the magnitude of roll damping derivatives has further increased by 20% with the increase in the angle of incidence. At higher sweep angles, the rate of decrease in roll damping derivative has come down as compared to the lower sweep angles from ten degrees to twenty degrees.

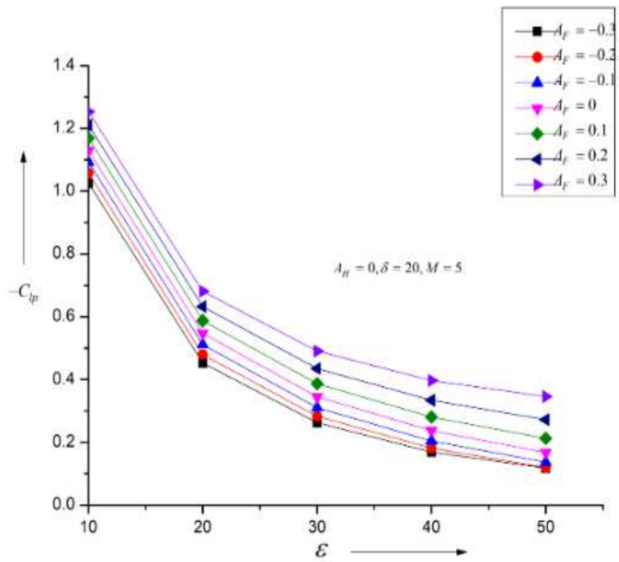

Figure 12: Rolling Derivative vs. Sweep Angle for δ = 200, M = 5

Figure 12 presents the rate of change in rolling derivative with a sweep angle for full sine wave for the angle of attack δ = 20^0.

These results are similar to that for the angle of attack five and fifteen degrees. It is evident from the expression of the rolling derivatives that trend will be linear with the increase in the angle incidence.

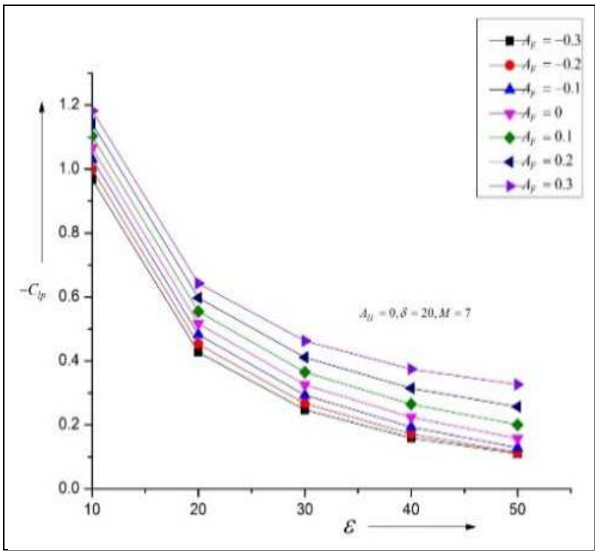

Figure 13: Rolling Derivative vs. Sweep Angle for δ = 200, M = 7

Figure 13 presents the rate of change in rolling derivative with a sweep angle for full sine wave for the flow deflection angle $\delta = 20^0$ at Mach 7. These results are similar to that for the angle of attack five and fifteen degrees. It is evident from the expression of the rolling derivatives that trend will be linear with the increase in the angle incidence. The increase in the Mach from 5 to 7 does not yield a substantial change in the roll damping derivative.

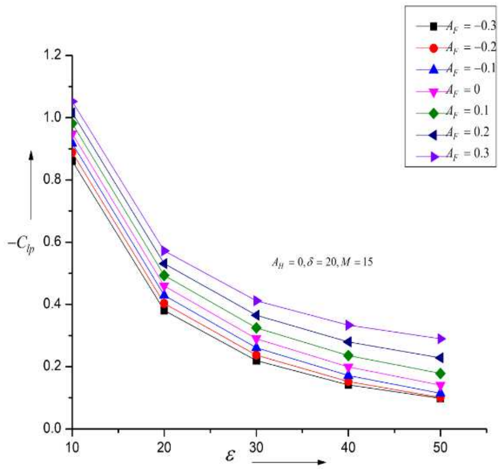

Figure 14: Rolling Derivative vs. Sweep Angle for δ = 200, M = 15

Figure 14 presents the rate of change of the rolling derivative with a sweep angle for full sine wave for the angle of attack $\delta = 20^0$. In this case, the alone angle of attack chosen is the highest ($\delta = 20^0$) before selecting this angle of attack we have ensured that the shock wave is attached. In this case, the angle of attack is the maximum, hence the magnitude of the roll damping derivative is also the maximum. Other trend remains the same as discussed above.

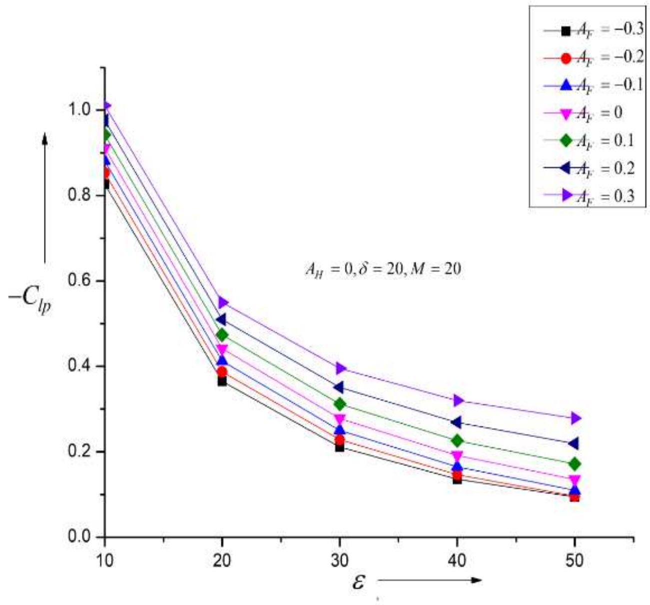

Figure 15: Rolling Derivative vs. Sweep Angle for δ = 200, M = 20

Figure 15 presents the rate of change of the rolling derivative with a sweep angle for full sine wave for the angle of attack $\delta = 20^0$ for Mach number 20. In this case, the angle of attack, as well as the inertia level, are maximum. The main contributor for the numerical values of the roll-damping derivative is the flow deflection angle of the flow. In this case the Mach M = 20, that is the highest value of the Mach of the present study. However, even at such high inertia, it does not yield in the substantial increase in the roll damping coefficient due to the rate of roll. As this value of the Mach, the flow has reached a steady state, and an increase in the Mach number will not result in any increment in the roll derivative. Other trend remains the same as discussed above.

4. CONCLUSIONS

From the discussions, which we had as above, we may draw the conclusions, which are as under

- It is found that the numerical value of the rolling moment coefficient is continuously decreasing with the increase in the sweep angle of the wing for a fixed value of the angle of attack and the amplitude of the full sine wave.
- There is a severe decrement in the rolling moment coefficient due to the rate of roll for sweep angles 100 to 200 due to the change in the surface area of the wing.
- With the increment in the inertia level of the flow, the rolling moment coefficient due to the rate of roll continues to decrease in magnitude. However, after the specific value of the inertia level, there is no reduction in the values of the rolling moment coefficient. Since the inertia level has reached a steady state level due to the increment in inertia level and hence the independent Mach number principle is attained.
- Due to an increase in the amplitude of the full sine wave, there is a progressive increment in the numerical values of the rolling moment coefficient due to the rate of a roll since the increase in the amplitude of the sine wave will increase the surface area.

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